POINT CONTACT TRANSDUCER OF WAVEGUIDING STRUCTURE FOR HIGH-FREQUENCY OPERATION

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Abstract

Time-of-flight measurements with point-like contact transducers have successfully been applied for the detection of anisotropy, and for in situ measurements of film thickness and temperature. The operation frequency range of the pin transducers made so far was, however, restricted at several hundreds of kHz. This paper presents a new type of Hertzian-contact transducer of waveguiding structure operating in the MHz range. The transducer is composed of a fused quartz tube and a radially-polarized annular piezoelectric element bonded to one of its ends. The edge-bonded shear-wave transducer effectively excites a surface wave on the interior surface of the tube. A small bullet pin made of quartz is inserted and fixed on the other end of the tube to make a point contact and transmit the wave energy to a specimen to be inspected. Using a pair of these transducers, we have succeeded in the excitation and detection of surface acoustic waves as well as Lamb waves in the 3MHz frequency range.

1. Introduction

Hertzian-contact pin transducers have been used as a new method for the excitation and detection of Lamb waves in plates [1]. The transducer is composed of a piezoelectric cylinder combined with a buffer rod whose end is sharpened like a pin to make a point contact to the solid plate under test. Time-of-flight measurements with these point-like contact transducers have successfully been applied for the detection of anisotropy, and for in situ measurements of film thickness and temperature. For measuring surface wave velocities and/or evaluating thickness of very thin films on a substrate, the transducers need to be operated at higher frequencies such as the MHz range. However, the operation frequency range of the pin transducers made so far was actually restricted at several hundreds of kHz. This was because the buffer rod had to be designed to have a diameter smaller than the wavelength so that it would support only a single, low dispersive length-extensional mode. This restriction on the wavelength-to-diameter ratio brought about difficulties in fabricating pin transducers suitable for high frequency operation.

In this paper we will present a new type of Hertzian-contact transducer of waveguiding structure operating in the MHz range. The transducer is composed of a tube with a radially-polarized annular piezoelectric disk on one end and a bullet pin on the other end. We will show results of some preliminary experiments of excitation and detection of acoustic waves carried out using a pair of these transducers at 3MHz range.

2. Transducer configuration

The ultrasonic time-of-flight measurement system using a pair of Hertzian-contact pin transducers is illustrated in Fig.1 [1]. The transducer is composed of a piezoelectric cylinder combined with a buffer rod whose end is sharpened like a pin to make a point contact to a solid plate. In this configuration the buffer rod must transmit a broad-band, pulsive wave generated by the piezoelectric cylinder to the sample plate, and

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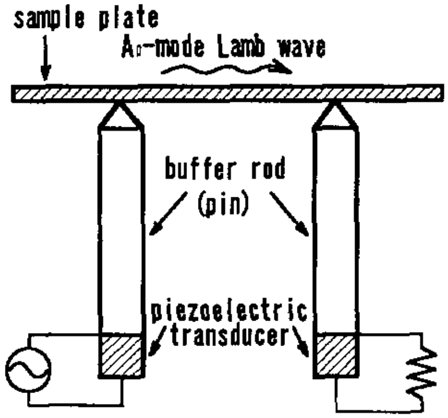

Fig.1 Time-of-flight measurement system with point-contact transducers.

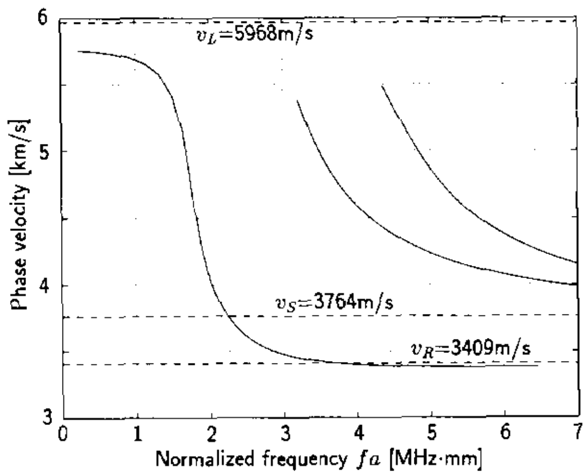

Fig.2 Phase velocity dispersion curves for symmetric modes in a fused quartz rod of diameter $2a$.

vice versa. Therefore, it is required that the rod vibrates in a single, least dispersive length-extensional mode.

Figure 2 shows the phase velocity dispersion curves for the symmetric modes in a fused quartz rod of diameter $2a$. Here, the horizontal axis is the product of frequency f and the rod radius a. In order that the buffer rod may work at the low dispersive region ($fa \leq 1$) of the first branch, the diameter of the rod must be a few times smaller than the wavelength. This restriction imposed on the wavelength-to-diameter ratio has made it difficult to fabricate pin transducers operating at high frequencies.

The new transducer configuration proposed

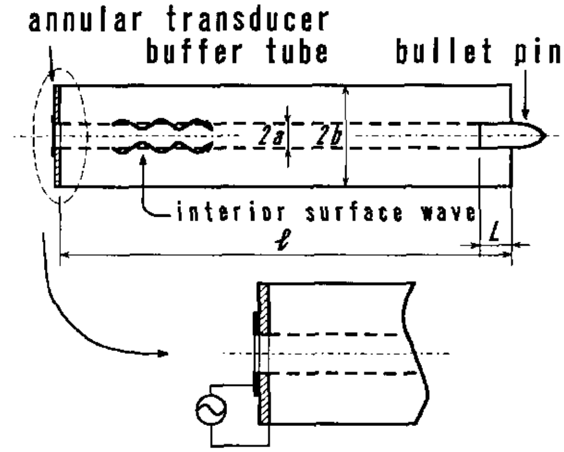

Fig.3 New configuration of point-contact transducer composed of waveguiding tube and bullet pin.

here is shown in Fig.3. The transducer employs a waveguiding tube [2],[3] instead of a rod at the buffer section, and a radially-polarized annular piezoelectric element is bonded to an end of the tube. The edge-bonded shear-wave transducer will effectively excite a surface wave on the interior surface of the tube. A small bullet pin is inserted and fixed on the other end of the tube, and it makes a point contact to a specimen to be inspected. The interior surface wave on the tube will be converted to an exterior surface wave on the bullet pin at the tube-pin boundary, and the wave energy will be transmitted to the specimen.

3. Fabrication of device and experiments

3.1 Waveguiding tube with edge-bonded transducer

Transducers were fabricated using fused quartz tubes of inner diameter $2a$=3.6mm, outer diameter $2b$=10mm, and length l=100mm as the buffer. Annular plates of PZT-5H having inner diameter of 3.6mm, outer diameter of 9.6mm, and thickness of 0.27mm were bonded to one end of the tubes. The radially polarized plate was designed to have the center frequency at around 3.6MHz. It has been known that a shear wave transducer bonded to a 90° edge of a substrate (edge-bonded transducer), excites a surface acoustic wave (SAW) efficiently if the elec-

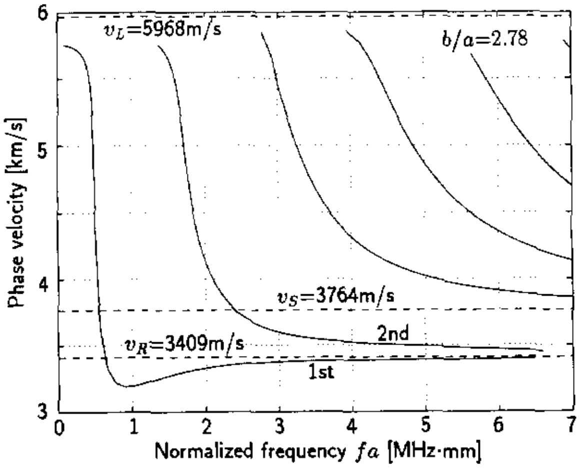

Fig.4 Phase velocity dispersion curves for symmetric modes in a fused quartz tube for b/a=2.78.

trode depth is set to about one wavelength of the SAW [4]. Since the wavelength of the interior SAW was estimated to be 0.96mm at 3.6MHz, an annular electrode of 1mm width was deposited on the inner end of the top surface of the PZT, whereas full metalization was made on the bottom surface.

Phase velocity dispersion curves for symmetric modes in a fused quartz tube are shown in Fig.4 for b/a of 2.78 [5]. Here, the horizontal axis is the product of frequency f and the inner radius a. For large fa, the first and the second branchs become the exterior and the interior surface wave modes, respectively [3]. The interior surface wave velocity is 3457m/s at 3.6MHz (fa=6.48MHz·mm) and the velocity dispersion seems to be small around this frequency.

3.2 SAW-SAW conversion at tube-pin boundary

First, some experiments were made to confirm SAW-to-SAW conversion at the tube-pin boundary. Two tubes were placed with their ends facing each other, and a fused quartz rod of 40mm length was inserted in between as shown in Fig.5. The rod had the same diameter (3.6mm) as the hole of the tubes so that it fitted well in the tubes. A small amount of water was put into the boudary by capillary action.

The optimum coupling length L in this case may be estimated using a simple model as follows: Suppose that two plane surfaces of a same

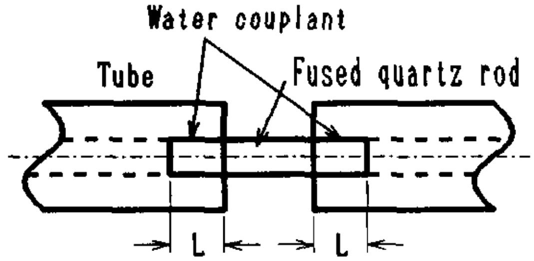

Fig.5 Experimental setup for examining the wave transmission through a coupling rod.

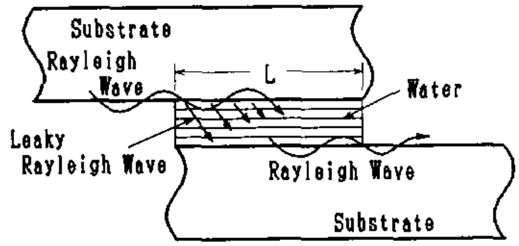

Fig.6 Mode conversion at two plane boundaries partially filled with water.

material are facing each other across a uniform gap, one section of which is filled with water over a length L as shown in Fig.6. A surface wave propagating on the upper plane will leak its energy into the water at the water-loaded section. The longitudinal wave in the water will impinge on the other surface at the Rayleigh angle and will be converted again into a surface wave. The propagation constant k_{LSAW} for the leaky surface wave can be written as

$$k_{LSAW} = \frac{2\pi}{\lambda_{LSAW}}(1 + j\alpha_N) \equiv \beta + j\alpha, \quad (1)$$

where, β and α are the phase and attenuation constants, respectively, λ_{LSAW} is the wavelength of the leaky SAW, and α_N is the normalized attenuation constant. It has been reported that the mode conversion will be optimum at $\alpha L \approx 1.26$ [6]-[8]. Applying $\alpha_N = 3.82 \times 10^{-2}$ for the quartz/water boundary [9], L is calculated at the frequency of 3.6MHz as follows:

$$L = \frac{1.26}{\alpha} = 1.26 \Big/ \left(\frac{2\pi\alpha_N}{\lambda_{LSAW}}\right) \approx 5 \text{ [mm]} \quad (2)$$

Figure 7 shows the variation of the transmitted signal intensity versus the coupling length L

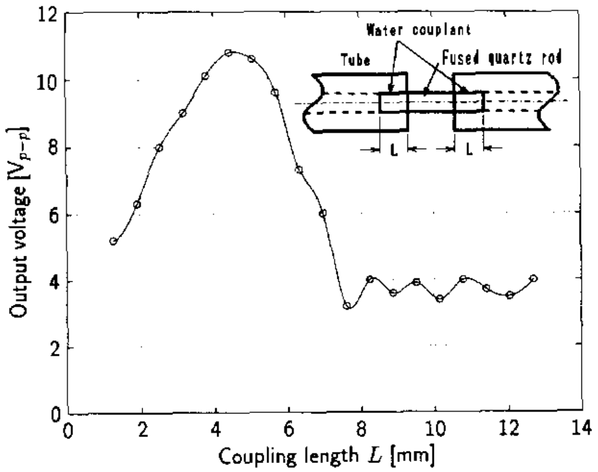

Fig.7 Variation of transmitted signal intensity for tube-rod-tube configuration.

for the tube-rod-tube configuration measured at 3.575MHz. Maximum transmission is obtained at $L \approx$5mm, as predicted theoretically.

Next, we examined the optimal value for L by a pulse-echo method when the rod was fixed to the tube. The rod was inserted and bonded with SALOL (Phenyl Salicylate) to the end of the tube, and the echo signal from the end of the rod was observed. Figure 8 shows the variation of the signal level versus the coupling length L. It is seen that, although the data points are few, maximum reflection is obtained at L=5mm.

Based on the experimental results described above, bullet pins were designed and fabricated. The pin had a diameter of 3.6mm, a length of 13mm, and the apex angle of about 60°. The top of the pin was polished and rounded to the radius of curvature of 100μm. The pin was inserted into the tube a distance of 5mm and fixed with SALOL.

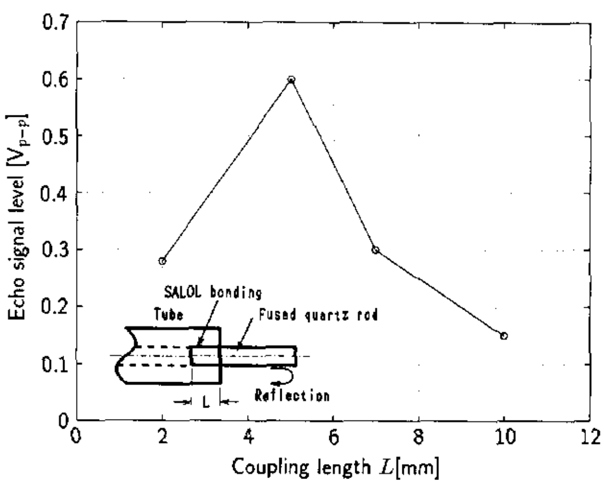

Fig.8 Variation of the signal intensity reflected back from the rod end. The rod is bonded to the tube with SALOL.

3.3 Transmission and reception of waves

Some preliminary experiments of transmission and reception of waves were made using a pair of the transducers. A 76.2mm-diameter Silicon wafer of 0.4mm thickness and a glass block of 97mm diameter and 17.3mm thickness were employed as samples. The transducer pins were separated from each other by 26.7mm and pressed gently against the samples. The exterior surfaces of the tubes were covered with clay to suppress unwanted modes. The transducer was excited with an RF-pulse voltage having the center frequency of 3.360MHz and the length of 1μsec.

Figure 9 shows the signal waveforms for the Si-wafer sample observed at the electric ports of the transducers. The upper trace is the signal at the transmitting port and the lower one at the receiving port. It is noted that Lamb waves launched by the transmitter are surely picked up by the receiver. The first arrival signal in the lower trace is the direct transmission between the pins, and the others are the multiple echoes bouncing from the periphery of the wafer.

Figure 10 shows the result obtained for the

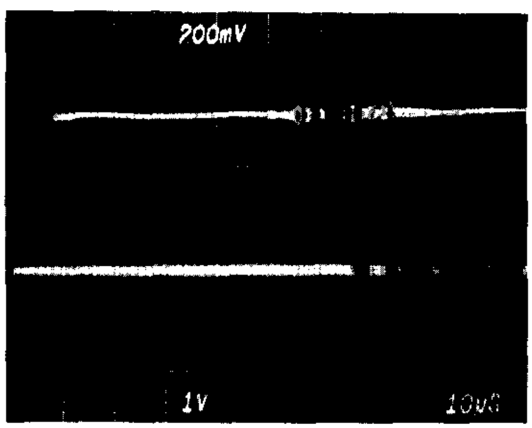

Fig.9 Signal waveforms obtained for a Si-wafer. Upper trace is at the transmitter and lower one at the receiver.

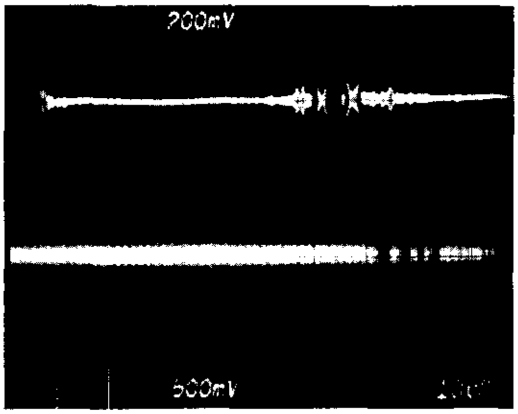

Fig.10 Signal waveforms obtained for a glass block. Upper trace is at the transmitter and lower one at the receiver.

glass block sample. The first arrival of the received signal was confirmed to be a SAW response because it faded away when a water drop was put on the transmission path. With the new type of point-contact transducers we have succeeded in the excitation and detection of SAWs which had been difficult with low-frequency point-contact transducers.

4. Conclusions

A new type of dry contact transducer for high-frequency operation has been developed. The transducer utilizes a waveguiding tube at the buffer section that carries a SAW on its interior surface. The interior SAW is converted into a SAW propagating on the exterior surface of a bullet pin that is making a point contact to a sample to be examined. With a pair of the transducers we have succeeded in the excitation and detection of surface acoustic waves on a glass block as well as Lamb waves in a Silicon wafer at the frequency of 3.36MHz.

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